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EFFECT OF TECHNOLOGICAL PARAMETER VARIATIONS ON THE STABILITY OF OPTICAL FIBER DRAWING

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A unidimensional model is developed including the equations of continuity and force equilibrium and a physical equation describing the state of glass melt in the fiber formation zone. Perturbations related to variations in the technological parameters are introduced into the solutions of equations determining a stable process, and possible deviations of the fiber radius are found.

Stringent requirements are imposed on optical fiber, including stability of fiber diameter.

Analytical models constructed in the context of fluid dynamics make it possible to predict the effect of variation of technological parameters (the rate and force of drawing, the temperature and viscosity in the deformation zone etc.) on stability of the drawing process.

The scheme of the process considered is shown in Fig. 1. Fiber *1* is drawn from glass melt *2* heated using a particular method (in a furnace, with a laser, etc.). According to the heating method, glass can exist as an intermediate product or as a melt flowing out of the opening in the crucible bottom.

The glass deformation zone can be divided into two zones: molding zone *a* and drawing zone *b*.

The molding zone is characterized by a fast narrowing and then it gradually passes into the drawing zone. In this zone the fiber characteristics are finally formed, which are influenced by perturbations both from zone *a* and from the drawing mechanisms beneath, for instance, in the form of mechanical vibrations.

Zone *b* can be studied using unidimensional models, including continuity and force equilibrium equations and a physical equation describing the state of the glass melt [1]. Without taking into account elastic properties of the glass melt, these equations have the following form [2]:

$$\frac{\partial(r^2)}{\partial t} + \frac{\partial(r^2 v)}{\partial z} = 0; \tag{1}$$

$$\rho\left(\frac{\partial(vr^2)}{\partial t} + \frac{\partial(v^2 r^2)}{\partial z}\right) = \frac{\partial(pr^2)}{\partial z}; \tag{2}$$

$$p = 3\mu\frac{\partial v}{\partial z}, \tag{3}$$

where $r(z, t)$ is the glass melt flow radius; t is the time; z is the axial coordinate; $v(z, t)$ is the glass melt flow velocity; ρ is the glass melt density taken to be constant; $p(z, t)$ is the stress in the considered flow section; μ is the dynamic viscosity.

Substituting expression (3) in condition (2), we obtain

$$\rho\frac{\partial(vr^2)}{\partial t} + \rho\frac{\partial(v^2 r^2)}{\partial z} - 3\frac{\partial(\mu r^2 \partial v / \partial z)}{\partial z} = 0. \tag{4}$$

The stationary variants (1) and (4) have the following form:

$$r^2 v = Q = \text{const}; \tag{5}$$

$$3\mu r^2\frac{\mathrm{d}v}{\mathrm{d}z} - \rho v^2 r^2 = C, \tag{6}$$

where C is the integration constant.

Without taking into account the inertia term, Eq. (6) can be represented using expression (5) in the form

$$\frac{\mathrm{d}v}{v} = N\mathrm{d}z, \tag{7}$$

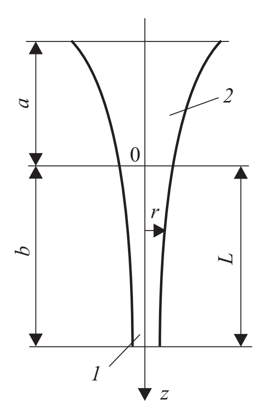

Fig. 1. Glass melt deformation zone.

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where $N = \frac{C}{3\mu r_0^2 v_0}$; ρ_0 and v_0 are the radius and the flow velocity, respectively, at $z = 0$.

Equations (5) and (7) make it possible to determine the variations of the flow velocity along the drawing zone and the shape of this zone. The length of the drawing zone is L. At $z = L$ the flow velocity is equal to the drawing velocity v_d, which is generated by the drawing mechanism.

Let us assume that in the drawing zone $\mu = \text{const}$. Then from Eqs. (5) and (7) we get

$$v = v_0 \exp(\xi \ln k); \tag{8}$$

$$r = r_0 \exp\left(-\xi \frac{\ln k}{2}\right), \tag{9}$$

where $\xi = z/L$; $k = v_d/v_0$ is the neck coefficient.

The solutions obtained describe a stable drawing process.

To estimate the effect of variations in the technological parameters on the stability of the drawing process, let us introduce perturbations of the first order for the radius $\tilde{r}$, velocity $\tilde{v}$, and viscosity $\tilde{\mu}$, and let us seek the first-order solutions of Eqs. (1) and (4) in the form

$$\begin{cases} r_{(1)} = r(z)[1 + \tilde{r}(z,t)]; \\ v_{(1)} = v(z)[1 + \tilde{v}(z,t)]; \\ \mu_{(1)} = \mu(z)[1 + \tilde{\mu}(z,t)], \end{cases} \tag{10}$$

where $r(z)$, $v(z)$, and $\mu(z)$ are solutions determining a stable process.

Substituting expression (10) in condition (1) and neglecting terms of the second order of smallness, we obtain

$$\frac{1}{v}\frac{\partial \tilde{r}}{\partial t} + \frac{1}{2}\frac{\partial \tilde{v}}{\partial z} + \frac{\partial \tilde{r}}{\partial z} = 0. \tag{11}$$

Without considering the inertia term, Eq. (4) after substituting conditions (10) into it will take the form

$$\tilde{\nu}_z \frac{v}{v_z} + \tilde{v} + 2\tilde{r} + \tilde{\nu} = P(t), \tag{12}$$

where $\tilde{\nu}_z = \frac{\partial \tilde{\nu}}{\partial z}$; $v_z = \frac{\partial v}{\partial z}$; $\nu = \frac{\mu}{\rho}$ is the kinematic viscosity; $P(t)$ is a certain arbitrary time function.

Equations (11) and (12) can be regarded as perturbation equations. The solution of these equations depends on the problem setting. For example, let us set the viscosity perturbation $\tilde{\nu}$ caused by temperature fluctuations and let us find the respective perturbations $\tilde{r}$ of the fiber radius. For this purpose we substitute solutions (8) and (9) for a stable process into Eqs. (11) and (12). As a consequence we obtain

$$\tilde{r}'' + \dot{\tilde{r}}' e^{-2\alpha} = \tilde{\nu}', \tag{13}$$

where $\tilde{r}'' = \frac{\partial^2 \tilde{r}}{\partial \alpha^2}$; $\dot{\tilde{r}}' = \frac{\partial^2 \tilde{r}}{\partial t \, \partial \alpha}$; $\alpha = \xi \ln \frac{k}{2}$; $\tilde{\nu} = \frac{\partial \tilde{\nu}}{\partial z}$.

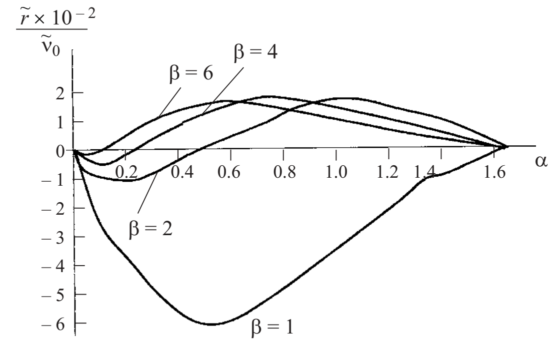

Fig. 2. The effect of viscosity on the deviation of normalized fiber radius.

Solutions of Eq. (13) depend on the boundary conditions and on the form of the function determining the viscosity perturbation.

Let us assume that the conditions of feeding glass melt into the drawing zone and gripping the drawn fiber do not change. Then one can take

$$\tilde{r}(0) = \tilde{r}(\alpha_L) = 0, \tag{14}$$

where α_L is a parameter correlating with $\xi = 1$.

Let us choose the exponent as the function determining the viscosity variation. Let us assume that there is no perturbation at $\alpha = 0$. Viscosity perturbation is determined by the function

$$\frac{\tilde{\nu}}{\tilde{\nu}_0} = \alpha e^{-\beta\alpha}, \tag{15}$$

where $\tilde{\nu}_0$ and β are parameters determining the disturbance amplitude.

Let us consider the stationary variant of Eq. (13). In this case the perturbation $\tilde{r}$ normalized with respect to $\tilde{\nu}_0$ for function (15) will take the form

$$\frac{\tilde{r}}{\tilde{\nu}_0} = -\frac{1}{\beta} e^{-\beta\alpha}\left(\frac{1}{\beta} + \alpha\right) + C_1\alpha + C_2, \tag{16}$$

where C_1 and C_2 are integration constants determined by boundary conditions (14):

$$\begin{cases} C_1 = \frac{1}{b}\left[e^{-\beta b}\left(\frac{1}{\beta} + b\right) - \frac{1}{\beta}\right]; \\ C_2 = \frac{1}{\beta^2}, \end{cases} \tag{17}$$

where $b = \ln(k/2)$.

Figure 2 shows the results of calculation of the normalized disturbance of radius $\tilde{r}/\tilde{\nu}_0$ based on expressions (16)

and (17) for different values of β. Let us correlate the maximum disturbance of viscosity $\tilde{\nu}_{max}$ and radius $\tilde{r}_{max}$ and derive a relationship based on the calculation results: $\tilde{\nu}_{max}/\tilde{r}_{max} \equiv n$: $\beta = 1$, $n \cong 6$; $\beta = 2$, $n = 9.2$; $\beta = 4$, $n = 4.6$; $\beta = 6$, $n \cong 3.8$.

In the most favorable case ($\beta = 2$) a 10% deviation of viscosity from a preset value will produce an approximately 1% deviation from the preset fiber radius, and in the worst case ($\beta = 6$) an approximately 3% deviation of the radius.

Thus, using Eqs. (11) – (13), it is possible to estimate the effect of the perturbation of the drawing velocity $\tilde{v}$ on the deviation of the fiber radius $\tilde{r}$.

REFERENCES

1. P. G. Loitsyanskii, *Mechanics of Fluid and Gas* [in Russian], Nauka, Moscow (1987).
2. V. P. Uvarov and I. K. Bakharev, "Stabilization of drawing of thin glass rods," *Steklo Keram.*, Nos. 5 – 6, 14 – 15 (1994).